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GEOCHEMICAL SIGNATURES OF MELTWATER IN MOLLUSC SHELLS FROM ANTARCTIC COASTAL AREAS DURING THE HOLOCENE

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Abstract: Compositional, crystallographic and isotopic characteristics in calcitic shells of the scallop, *Adamussium colbecki*, were analyzed to interpret meltwater impacts in Antarctic coastal areas during the last 10000 years. Adjacent to glacial meltwater streams in West McMurdo Sound, live scallops had complementary trace element, unit cell volume and oxygen isotope profiles from 6 to 27 m depth. Shell $\delta^{18}O_c$ (PDB) values, which were used to predict the $\delta^{18}O_w$ (SMOW) of the ambient seawater, produced estimates that accurately described the seawater isotopic composition and glacial meltwater volume in this coastal area. Radiocarbon reservoir corrections, based for the first time on Antarctic molluscs collected before 1945, were developed to constrain the Holocene chronologies of fossil *Adamussium* analogs. The similar 50‰ offset between the pre-nuclear and post-nuclear $\Delta^{14}C$ concentrations, in both Antarctic molluscs and seawater south of 60°S, indicates that a 1400 ± 100 year reservoir correction is generally appropriate for Antarctic molluscs. Considering the temporal context of the shell $\delta^{18}O_c$ (PDB) values in *Adamussium* fossils from Terra Nova Bay, it is suggested that there was more meltwater along the Victoria Land Coast during the middle Holocene than at present. Together, these molluscan shell analyses provide a geochemical framework for assessing the responses of the Antarctic ice sheet margins to climate changes and their contribution to sea level during the Holocene.

Key words: crystrallography, fossils, oxygen isotopes, radiocarbon, raised beaches, trace metals

1. Introduction

Nearshore marine species around Antarctica exist in a transition zone between continental ice sheets and the ocean. In this circumpolar region, ice-sheet advances lowered sea level and eliminated coastal marine habitats. Retreating ice sheets, in contrast, raised sea level and influenced the isostatic uplift of coastal marine habitats. Marine species which later emerged as fossils in raised beaches reflect this later history of ice-sheet melting (Appendix 1). The purpose of this manuscript is to evaluate the geochemical records of meltwater which are contained in the shells of a representative circumpolar species with abundant distributions in Antarctic nearshore marine environments during the current climate period (the Holocene) which began 10000 years ago.

The magnitude and timing of Holocene sea-level impacts from Antarctica along with their climatic forcing are not well constrained. Data from emerged beaches suggest that the Antarctic ice sheets remained virtually unchanged after 8000 yr B.P. and their contribution to Holocene sea-level rise was less than 2.5 m (COLHOUN *et al.*, 1992). In contrast, global isostatic models suggest that the Antarctic ice sheets must have contributed 25 m (CLARK and LINGLE, 1979; NAKADA and LAMBECK, 1988; TUSHINGHAM and PELTIER, 1991) to the sea-level rise of the Holocene (FAIRBANKS, 1989).

It is known from ice-core records that the "climatic optimum" in Antarctica occurred between 10000 and 6000 years ago (LORIUS *et al.*, 1979; CIAS *et al.*, 1992). During this period, marine sedimentation in East Antarctica (DOMACK *et al.*, 1991a) and glacial stratigraphy in West Antarctica (INGOLFSSON *et al.*, 1992) were influenced by ice sheet advances which may occur under warmer climate conditions (JACOBS, 1992). In contrast, early-middle Holocene deglaciation is suggested by sedimentary, glaciological and emerged species' records along the coasts of East Antarctica (DOMACK *et al.*, 1991b; ADAMSON and COLHOUN, 1992; FITZSIMONS and DOMACK, 1993; GOODWIN, 1993) and West Antarctica (DENTON *et al.*, 1989; CLAPPERTON and SUGDEN, 1990). Although difficult to resolve after the Last Glacial Maximum, deep-sea sediment records further suggest that there was Antarctic ice-sheet melting during the Holocene (LABEYRIE *et al.*, 1986). It also is possible that the West Antarctic Ice Sheet fluctuated during the Holocene (SUGDEN and CLAPPERTON, 1980). Whatever the environmental history, during periods of ice-sheet retreat, pulses of meltwater would have directly impacted Antarctic coastal areas and the geochemistry of nearshore marine species.

The Antarctic scallop (*Adamussium colbecki*) is a representative coastal marine species because of its circumpolar distribution, large shells, high densities and exclusively marine life-history in nearshore habitats (BERKMAN, 1990, 1991). Importantly, *Adamussium* also is a common and well-preserved marine fossil in adjacent Holocene beaches around the continent (BERKMAN, 1992, Appendix 2). Together, these living and fossil scallop analogs provide an experimental framework for interpreting meltwater variability associated with changes in the Antarctic ice sheets during the last 10000 years.

2. Materials and Methods

2.1. Live scallops across a nearshore meltwater gradient

Live *Adamussium* were collected during the 1986–87 austral summer across a depth gradient from 6 to 27 m at Explorers Cove (77°35′S, 163°40′E) in West McMurdo Sound, Antarctica, in an area which is impacted by seasonal glacial runoff (BERKMAN, 1991, 1994). The impacts of meltwater on scallop shell geochemistry across this spatial gradient are analogous to the geochemical records which may exist among fossil scallop shells across the Holocene (BERKMAN *et al.*, 1992). Oxygen isotopic (KRANTZ *et al.*, 1988), trace element (RUCKER and VALENTINE, 1961; EISMA *et al.*, 1976), and crystallographic (LORENS and BENDER, 1977) analyses were conducted to assess the geochemical sensitivity of the live *Adamussium* shells as records of meltwater input.

Unbroken paired-valves from four depths were selected to evaluate the relative impacts of the seasonal glacial runoff. At 6 m, 10 m and 21 m depths, three shells from November 1986 and three from January 1987 were analyzed. At 27 m depth, three shells only from January 1987 were analyzed. Similar shell sizes among the 21 scallops were selected (74.9 ± 2.0 mm) to avoid any geochemical variations associated with their ontogeny (ROSENBERG, 1980).

Each of the paired shell valves was gently cleaned with a wire brush and sonicated for one minute to remove epizoic species and surface debris. The valves then were dipped into dilute HCl, dilute $NaHCO_3$ and finally rinsed with distilled water to remove any remaining organic residue on the shell surfaces.

A 2-mm band was abraded with an high-speed drill along the peripheral margin of each of the 42 shell valves to produce the powders for the oxygen isotope analyses. These powders were not roasted (RYE and SOMMER, 1980), but are considered to be comparable to those that have been because the amount of organic material and aragonite in the calcitic *Adamussium* shells is negligible (BERKMAN, 1991). Each peripheral margin sample weighed less than 0.5 g and was reacted in concentrated phosphoric acid at 60°C (RYE and SOMMER, 1980; KRANTZ *et al.*, 1987) prior to being measured with a Finnagan MAT-250 at Shizuoka University, Japan. The precision of these analyses was better than 0.1‰ (SANTOSH and WADA, 1993).

Reported in δ notation, isotopic ratios of $^{18}O/^{16}O$ from the peripheral margin of the shells were used to interpret the temperature and meltwater input at Explorers Cove during the most recent summer period when the *Adamussium* were collected. Two meltwater samples from Wales Stream and nine seawater samples from the upper 5 m in the study area (BERKMAN, 1991, 1994) at Explorers Cove were collected during the 1987/1988 austral summer to determine whether the *Adamussium* shells were precipitated in isotopic equilibrium with their environment.

The remaining material of each shell valve, which weighed between 1 and 2 g, was homogenized with an automatic grinder for 10 min to produce equal-volume powders for the trace element and crystallographic analyses. As described by BERKMAN *et al.* (1992), the trace element concentrations were determined by atomic absorption at Nagoya University and the unit cell volumes were measured by X-ray diffraction at the National Institute of Polar Research in Japan. These bulk-shell analyses provided independent geochemical perspectives on the isotopic analyses to interpret whether meltwater impacted the composition of the scallop shells during their lifetime.

2.2. *Microscale shell transects*

Three *Adamussium* shells, between 75 mm and 85 mm in height, were mechanically cleaned only (see above). The shell surfaces of the upper valves then were sub-sampled with a dental drill at 2 mm intervals along 20 mm transects from the peripheral margin toward the umbo (WADA, 1988; OBA *et al.*, 1992). Each sub-sample provided approximately 1 mg which was prepared for the oxygen isotope analyses (see above). Two of the shells, from 6 m and 21 m depths, were analyzed with a Finnagan MAT-251 with a precision better than 0.1‰ at Hokkaido University, Japan. The other shell from 6 m depth was analyzed at the Shizuoka facility. The purpose of these oxygen isotope transects was to determine whether hydrochemical cycles could be distinguished across the growing surfaces of the *Adamussium* shells.

2.3. Radiocarbon analysis of Antarctic molluscs

To determine an appropriate radiocarbon reservoir correction for Antarctic molluscan species (GORDON and HARKNESS, 1992), samples of molluscs which were alive before 1945 and not contaminated by nuclear fallout were dated. *Adamussium* valves that were collected in 1940 from 68°30′S, 67°00′W at a depth of 27 m (USNM 522464) and from 67°52′S, 67°17′W at a depth of 34 m (USNM 522467) were analyzed along with a sample of *Thracia meridionalis* which was collected in 1935 from 78°30′S 164°20′W at a depth of 490 m (USNM 613138). These specimens, which were obtained from the Smithsonian Institution, had paired valves with resiliums still attached, reflecting their live collection. Less than 0.2 g of material was taken from the upper valve of each shell along the peripheral margin which is monomineralic (*i.e.* only calcite).

The shells were cleaned thoroughly in an ultrasonic cleaner and then leached with dilute HCl to remove any surficial materials. The cleaned shell samples then were hydrolyzed with HCl, under vacuum, and the carbon dioxide was recovered. Because of the small sample volume, both of the samples were analyzed by accelerator mass spectrometry (AMS) at Geochron Laboratories, Cambridge, Massachusetts. Conventional radiocarbon ages, based on a half-life of 5568 years, were calculated after correcting for $\delta^{13}C$ (STUIVER and POLACH, 1977).

3. Results

3.1. Shell geochemistry: Trace elements

The overall ranking of trace element concentrations in the nearshore *Adamussium* shells was: Fe(72.0 ± 3.7 ppm) > Mn(14.9 ± 1.0 ppm) > Cr(12.6 ± 0.2 ppm) > Zn(9.6 ± 0.7 ppm) > Cu(5.0 ± 0.1 ppm). Among these trace elements, only the Fe and Zn concentrations (Figs. 1a and 1b) decreased significantly from 6 m to 27 m depth (Tables 1a and 1b).

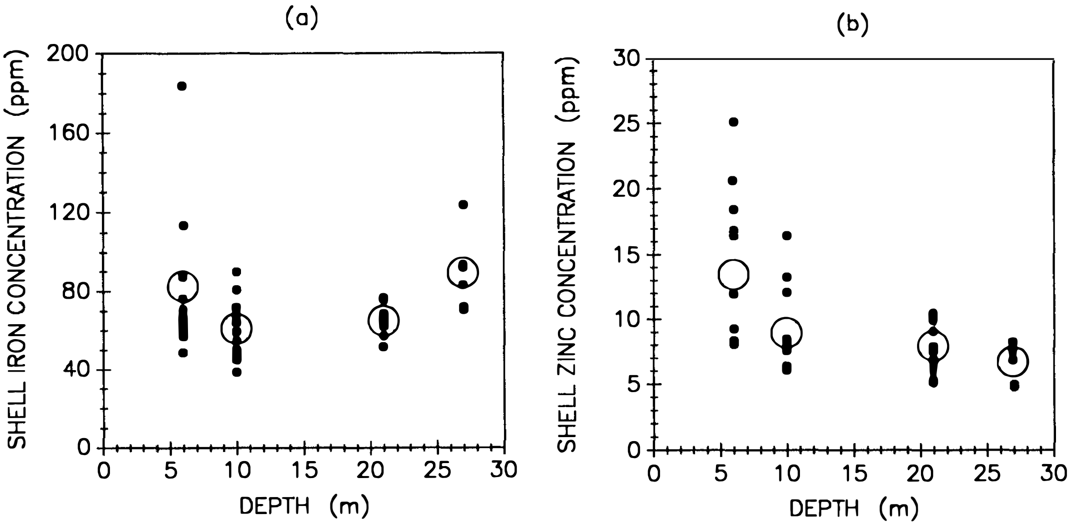

Fig. 1. Adamussium-*shell (a) iron and (b) zinc concentrations across a nearshore depth gradient adjacent to glacial meltwater stream runoff in Explorers Cove, Antarctica, during the 1986–87 austral summer. Individual values (filled circles) and the means (open circles) for each depth are shown.

Table 1a. Analysis of variance effect of depth on shell iron concentration.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio	Probability
Depth	140.430	3	1713.477	3.337	0.029
Error	19510.578	38	513.436		

Table 1b. Analysis of variance effect of depth on shell zinc concentration.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio	Probability
Depth	268.786	3	89.595	5.627	0.003
Error	605.103	38	15.924		

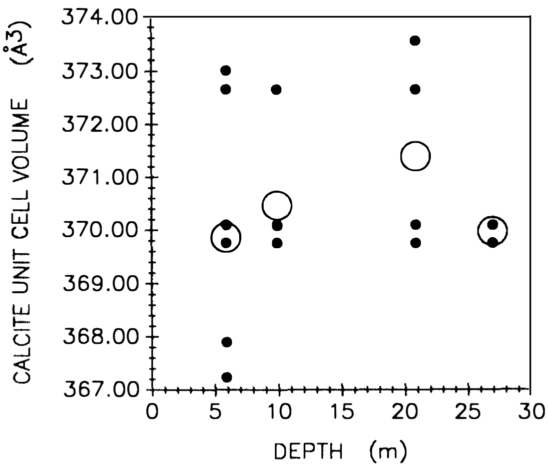

Fig. 2. Adamussium-*shell unit cell volumes across a nearshore depth gradient adjacent to glacial meltwater stream runoff in Explorers Cove, Antarctica, during the 1986–87 austral summer. Individual values (filled circles) and the means (open circles) for each depth are shown.*

3.2. *Shell geochemistry: Calcite unit cell volumes*

Based on the hexagonal crystal system (Reeder, 1983), the unit cell volumes of the calcitic *Adamussium* shells were calculated according to (Berry *et al.*, 1983):

$$V = a^2 c \sin 60^\circ \,, \quad (1)$$

where a and c are the axial dimensions of the unit cells. These unit cell volumes (Fig. 2), which depend on the integrated composition of the intracrystalline elements in the *Adamussium* shells (Berkman *et al.*, 1992), had mean values that were all larger than those of pure calcite which is 367.9 A^3 (Swanson and Fuyat, 1953). The unit cell volumes also varied significantly across the nearshore depth gradient at Explorers Cove (Table 2) and appeared to be inversely related to the concentrations of Fe and Zn (Tables 1a and 1b).

Table 2. Analysis of variance effect of depth on calcite unit cell volume.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio	Probability
Depth	16.138	3	5.379	2.950	0.045
Error	69.031	38	1.824		

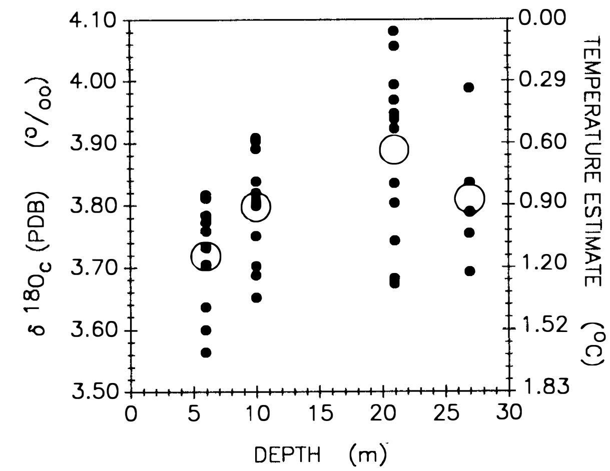

Fig. 3. Adamussium-*shell oxygen isotope ratios across a nearshore depth gradient adjacent to glacial meltwater stream runoff in Explorers Cove, Antarctica, during the 1986–87 austral summer. Temperature estimates were derived from eq. (2) (see text). Individual values (filled circles) and the means (open circles) for each depth are shown.*

Table 3. Analysis of variance effect of depth on shell $\delta^{18}O_c$ (PDB).

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio	Probability
Depth	0.174	3	0.058	5.286	0.004
Error	0.417	38	0.011		

3.3. Shell geochemistry: Oxygen isotopes

The oxygen isotopic ratios from the live *Adamussium* shell margins (Fig. 3) match those measured from an independent study (BARRERA *et al.*, 1990) and were found to increase significantly with depth at Explorers Cove (Table 3). Based on the oxygen isotope values (Fig. 3), paleotemperature estimates (RYE and SOMMER, 1980) were calculated from the isotopic equilibrium equation of EPSTEIN *et al.* (1953) as modified by CRAIG (1965):

$$T°C = 0.13\,(\delta^{18}O_c - \delta^{18}O_w)^2 - 4.2\,(\delta^{18}O_c - \delta^{18}O_w) + 16.9\,, \qquad (2)$$

where $\delta^{18}O_c$ (PDB) is the oxygen isotopic composition of shell calcite and $\delta^{18}O_w$ (PDB) is the isotopic composition of ambient seawater. The data from JACOBS *et al.* (1985) were used to calculate an average $\delta^{18}O_w$ (SMOW) for the upper 20 m of the Ross Sea which was −0.39‰. This value was converted to the PDB scale according to RYE and SOMMER (1980):

$$\delta^{18}O_w(PDB) = \delta^{18}O_w(SMOW) - 0.22\,, \qquad (3)$$

and was determined to be −0.61‰. Substituting the appropriate values into eq. (2) reasonably predicts that mean seawater temperatures decreased around 0.5°C between 6 m and 21 m depth during the summer (Fig. 3). However, the absolute magnitudes of the temperature estimates in Fig. 3 are questionable given that seawater temperatures higher than −0.2°C have not been measured in McMurdo Sound (LITTLEPAGE, 1965; BARRY, 1988).

Using −0.2°C as the maximum temperature for Explorers Cove, summer $\delta^{18}O_w$ (PDB) values at the different depths were predicted with a modified quadratic from of eq. (2):

$$X = \frac{-4.2 \pm \sqrt{17.64 - [0.52 \times (16.9 - T°C)]}}{0.26}\,, \qquad (4)$$

where $X = \delta^{18}O_c$ (PDB) $- \delta^{18}O_w$ (PDB). After solving for $\delta^{18}O_w$ (PDB) and converting to $\delta^{18}O_w$ (SMOW), as indicated by eq. (3), $\delta^{18}O_w$ (SMOW) values from −0.84‰ to −0.67‰ were calculated with the *Adamussium* shells from 6 m to 27 m depth (Fig. 3). This range of predicted oxygen isotope values overlaps with the actual $\delta^{18}O_w$ (SMOW) values which ranged from −1.04‰ to −0.79‰ in summer seawater samples from the area where the shells were collected (L. G. THOMPSON, unpublished data). Two $\delta^{18}O_w$ (SMOW) values from the summer glacial meltwater in Wales Stream which flows into Explorers Cove were determined to be −29.68‰ and −28.87% (L.G. THOMPSON, unpublished data).

The three oxygen isotope transects across the growing margin of the *Adamussium* shells reflect hydrochemical cycles in the nearshore marine environment at Explorers

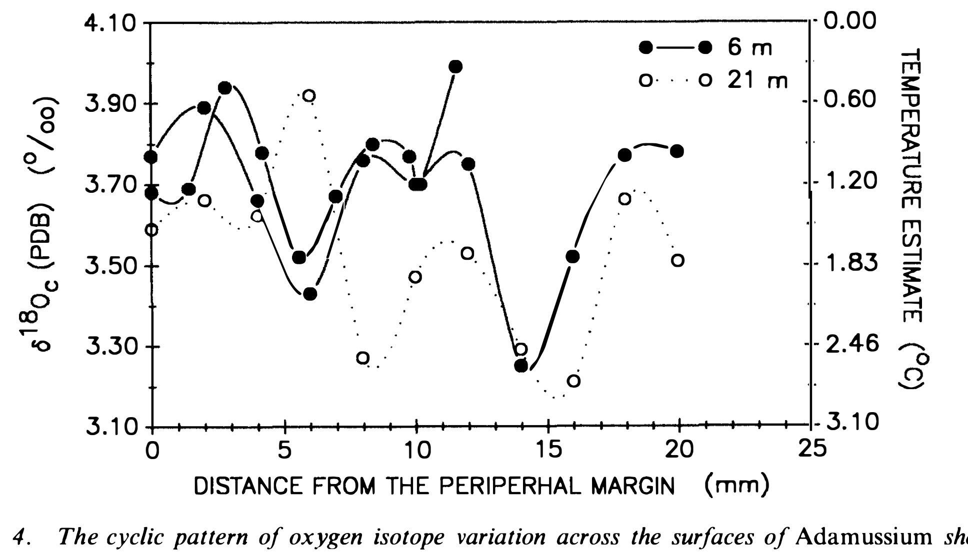

Fig. 4. The cyclic pattern of oxygen isotope variation across the surfaces of Adamussium *shells from 6 m and 21 m depths which were collected alive at Explorers Cove, Antarctica, during the 1986–87 austral summer. Temperature estimates were derived from eq. (2) (see text).*

Cove (Fig. 4). There is close agreement between the patterns across the two shells from 6 m depth, even though the analyses were conducted in different laboratories. In all three samples, oxygen isotopic concentrations appear to cycle every 5–10 mm across the shell surfaces. In addition, the period of these oxygen isotope cycles appears to increase across the shell surface with distance from the peripheral margin. This oxygen isotope periodicity is suggestive of an annual hydrochemical cycle, as indicated by the shell growth rates of *Adamussium* which gradually decrease with increasing shell size and are around 5 mm yr^{-1} for 70–80 mm scallops at Explorers Cove (BERKMAN, 1990).

Based on the amplitude of the oxygen isotope cycles (Fig. 4), it was estimated (eq. (2)) that their environmental temperatures varied by more than 2.5°C. This estimated temperature range exceeds the actual seawater temperature range based on measurements in McMurdo Sound which vary annually from around −1.9°C to −0.2°C (LITTLEPAGE,

Table 4. Radiocarbon ages of pre-nuclear Antarctic marine mollusc shells.

Laboratory number	Mollusc speies[1]	Location	Latitude	Longitude	Date of collection	^{14}C age (yr BP)[2]	Reference
GX 18581	Ac	Peninsula	68°30′S	67°00′W	1940	1476±39	this paper
GX 18582	Ac	Peninsula	67°52′S	67°17′W	1940	1416±40	this paper
GX 19205	Tm	Bay of Whales	78°30′S	164°20′W	1935	1278±62	this paper
					Mean	1390±83	

(1) Ac *Adamussium colbecki*, Tm *Thracia meridionalis*.
(2) Year Before Present (mean ± 1 standard deviation).

Table 5. Radiocarbon ages of post-nuclear Antarctic marine mollusc shells.

Laboratory number	Mollusc species[1]	Location	Latitude	Longitude	Date of collection	^{14}C age (yr BP)[2]	Reference
GaK 6789b	Ne	Soya Coast	69°03′S	39°35′E	1975	1300± 90	YOSHIDA and MORIWAKI, 1979
SUA 1235	Le	Vestfold Hills	68°35′S	78°50′E	1978	950±110	PICKARD and ADAMSON, 1983
ZDL 84	Le	Vestfold Hills	68°35′S	77°50′E	1981	1312± 65	ZHANG *et al.*, 1983
GX 12743	Ac	Terra Nova Bay	74°19′S	165°05′E	1986	920± 40	BARONI and OROMBELLI, 1987
R.553	Ac	Ross Sea	77°25′S	169°28′E	1959	920	RAFTER *et al.*, 1972
QL 98	Ac	McMurdo Sound	77°38′S	166°25′E	1970's	850± 50	STUIVER *et al.*, 1981
QL 996	Ac	McMurdo Sound	77°38′S	166°25′E	1970's	950± 50	STUIVER *et al.*, 1981
Lu 3102	Le	Peninsula	64°10′S	57°45′W	1987	820± 50	BJORK *et al.*, 1991
Lu 3103	Ye	Peninsula	64°10′S	57°45′W	1987	860± 50	BJORK *et al.*, 1991
Lu 3104	Nc	Peninsula	64°10′S	57°45′W	1987	920± 80	BJORK *et al.*, 1991
					Mean	980±168	

(1) Ac *Adamussium colbecki*, Le *Laternula elliptica*, Ne *Neobuccinum eotoni*, Ye *Yoldia eightsii*, Nc *Nacella concinna*.
(2) Year Before Present (mean ± 1 standard deviation).

1965; BARRY, 1988).

3.4. Radiocarbon reservoir correction for Antarctic molluscs

The mean radiocarbon age of the three coastal Antarctic molluscs from 1935 and 1940 was 1390±83 ^{14}C yr BP (Table 4). This mean "pre-nuclear" radiocarbon age is 400 years older than the 980±168 ^{14}C yr BP "post-nuclear" age which was derived from Antarctic molluscs collected after 1945 (Table 5). The offset between the $\Delta^{14}C$ values (as defined by BROECKER and PENG, 1982) of the pre-nuclear ($\Delta^{14}C \approx 160‰$) and post-nuclear ($\Delta^{14}C \approx 115‰$) molluscs in Tables 4 and 5, respectively, are in strong agreement with seawater radiocarbon measurements south of 60° South latitude which had $\Delta^{14}C$ values that varied around 50‰ between the periods before and after 1945 (BROECKER *et al.*, 1985).

4. Discussion

4.1. Geochemical signatures of meltwater

Glacial meltwater streams solubilize minerals from the Dry Valleys region (LYONS and MAYEWSKI, 1993) and are known to introduce Zn, Fe and Mn into coastal marine environments in higher concentrations than exist in seawater (BOSWELL *et al.*, 1967). Because meltwater is relatively buoyant compared to seawater, the highest trace element concentrations would be expected in shallow water as was revealed by the Fe and Zn concentrations in the *Adamussium* shells (Figs. 1a and 1b). The significant trend of decreasing trace element concentrations with depth (Tables 1a and 1b) was independently observed in an earlier analysis of nearshore *Adamussium* shells from Explorers Cove (BERKMAN *et al.*, 1992).

All of the trace element concentrations in the *Adamussium* shells in this study are lower than those analyzed by BERKMAN *et al.* (1992), which were mechanically cleaned but not dipped in acid. Such concentration differences suggest that some of the trace elements were removed from the shell surfaces by the acid preparation procedure in this study.

Nonetheless, there is an inverse relationship between the mean iron concentrations and unit cell volumes in the *Adamussium* shells from 6 m to 27 m depth (Figs. 1a and 2). These data indicate that there were isomorphic substitutions in the $CaCO_3$ matrix by trace elements (such as Fe, Mn, Cr, Zn and Cu) which have divalent cations with smaller ionic radii than Ca (BERRY *et al.*, 1983). The correspondence between the trace element concentrations and unit cell volumes demonstrates that the calcitic *Adamussium* shells contain geochemical imprints which can be directly related to glacial meltwater runoff.

Unit cell volumes represent the concentration of intracyrstalline elements in thermodynamically stable lattice sites (SWALIN, 1962). As opposed to intercrystalline elements which are subject to diagenesis (CURTIS and KRINSLEY, 1965), the unit cell volumes provide a geochemical basis for interpreting Holocene meltwater impacts from fossil *Adamussium* shells.

Oxygen isotope ratios in the *Adamussium* shells provide an independent geochemical perspective for interpreting meltwater input. The paleotemperature estimates (eq. (2))

of 0.05°C to 1.63°C for the seawater at Explorers Cove (Fig. 3) are unrealistic and suggest that the $\delta^{18}O_c$ (PDB) values of the shells were influenced by meltwater from local sources other than the sea ice (REDFIELD and FRIEDMAN, 1969).

Based on a −0.2°C temperature maximum for Explorers Cove and the $\delta^{18}O_c$ (PDB) values of the *Adamussium* shells (Fig. 3), $\delta^{18}O_w$ (SMOW) values were predicted (eqs. (3) and (4)). The close agreement between the predicted $\delta^{18}O_w$ (SMOW) values and those that were measured in Explorers Cove during the summer, as indicated by their overlap between −0.79‰ and −0.84‰, demonstrates that the *Adamussium* shells were growing in isotopic equilibrium with their environment. These predicted $\delta^{18}O_w$ (SMOW) values also were between 0.40‰ and 0.45‰ lower than the average $\delta^{18}O_w$ (SMOW) values in the upper 20 m of the Ross Sea, as measured by JACOBS *et al.* (1985). The excess $\delta^{18}O_w$ (SMOW), which could not be attributed to seawater temperatures above −0.2°C, must have been influenced by glacial meltwater runoff which had $\delta^{18}O_w$ (SMOW) values on the order of −30‰. The same conclusion about the impact of glacial meltwater is suggested by the oxygen isotope transects across the *Adamussium* shell surfaces (Fig. 4), which had an estimated temperature range that exceeded the measured temperature range in the environment.

As an independent check of the meltwater impact, $\delta^{18}O_c$ (PDB) values of the shells can be compared with their elemental compositions, which are known to strongly reflect salinities less than 25‰ (PILKEY and GOODELL, 1963). The similarity between the profiles of $\delta^{18}O_c$ (PDB) and unit cell volume (Figs. 2 and 3), along with their significant linear relationship from 6 m to 21 m depth (Fig. 5), demonstrates that the $\delta^{18}O_c$ (PDB) values in the *Adamussium* shells were affected by glacial meltwater impacts in Explorers Cove.

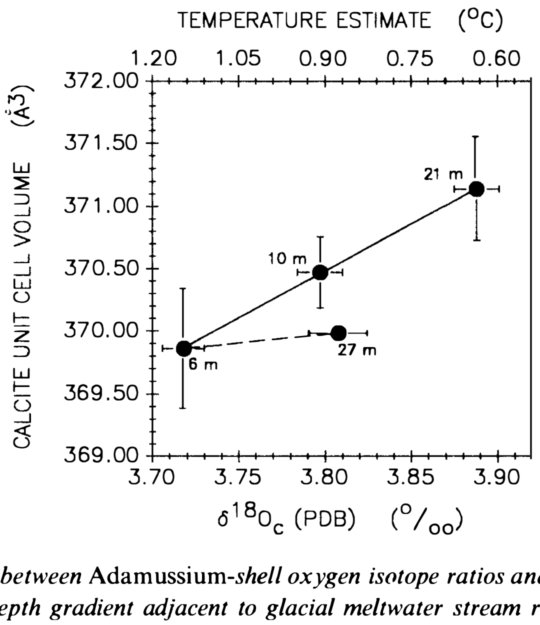

Fig. 5. Relationships between Adamussium-*shell oxygen isotope ratios and unit cell volumes across a nearshore depth gradient adjacent to glacial meltwater stream runoff in Explorers Cove, Antarctica, during the 1986–87 austral summer. Based on the mean values and their standard deviations, these two geochemical parameters were significantly related ($r^2 = 0.999$) between 6 and 21 m depth. The apparently anomalous point at 27 m depth may reflect the convective transport of meltwater down the steep slope which is at the mouth of the glacial streams in Explorers Cove.*

The apparently anomalous datum at 27 m depth in Fig. 4 may represent a physical process associated with double diffusive convection (GREGG, 1980; HUPPERT and TURNER, 1981) of meltwater down the steep slope where the glacial steams enter Explorers Cove. These data underscore the importance of assessing the physical processes which influence the geochemistry of modern shells as analogs for interpreting the paleo-environmental records in their adjacent fossils.

4.2. *Meltwater volume estimates*

Based on the predicted summer $\delta^{18}O_w$ (SMOW) values from the *Adamussium* shells, which ranged from $-0.84‰$ to $-0.67‰$ (see above), the volume of meltwater entering Explorers Cove can be estimated conservatively with a simple two-component mixing equation for a closed system:

$$V_{melt}O_{melt} + V_{sea}O_{sea} = (V_{melt} + V_{sea})O_{mix} , \quad (5)$$

where the volumes (V) and oxygen isotopic characteristics (O) of the meltwater streams (melt) and seawater in Explorers Cove (sea) are mixed (mix). As discussed above, the measured mean $\delta^{18}O_w$ (SMOW) values for the glacial meltwater streams at Explorers Cove and the seawater in the upper 20 m of the Ross Sea were $-29.28‰$ and $-0.39‰$, respectively. Lastly, the study area at Explorers Cove was estimated to be 2 km wide, 1 km across and 30 m deep with a volume of $0.06\,km^3$. The impact of sea ice melting or freezing on seawater oxygen isotopic characteristics was considered to be negligible (REDFIELD and FRIEDMAN, 1969). Consideration of any mixing with water from the Ross Sea would require a more complicated model, which only would increase the total seawater volume and glacial meltwater volume estimates in Explorers Cove.

Using the above input parameters, the total volume of glacial meltwater runoff into Explorers Cove during the summer was estimated to range from $0.59 \times 10^6\,m^3$ to $0.95 \times 10^6\,m^3$. The validity of this first approximation can be seen in relation to the total volume of the Onyx River in the adjacent Dry Valleys, which is the largest meltwater stream in Antarctica. Summer data from 1968 to 1988 indicate that the Onyx River had a maximum volume of $14.98 \times 10^6\,m^3$, a minimum of $0\,m^3$ and a mean of $3.78 \pm 3.49 \times 10^6\,m^3$ during this 20-year period (CHINN, 1993). These measurements demonstrate that the volume of meltwater into the nearshore area at Explorers Cove can be reasonably estimated based on the oxygen isotopic composition of *Adamussium* shells.

4.3. *Radiocarbon reservoir correction*

All of the geochemical analyses of Holocene fossils ultimately rely on accurate radiocarbon-age constraints. Previously, all of the radiocarbon reservoir corrections for Antarctic molluscs have been based on pre-nuclear seals and penguins which are known to have distinct $\delta^{13}C$ values (GORDON and HARKNESS, 1992). This study presents the first analysis of pre-nuclear radiocarbon ages from Antarctic molluscs.

The close agreement between the $\Delta^{14}C$ variation of pre-nuclear (Table 4) and post-nuclear (Table 5) mollusc shells and seawater south of 60° South latitude (BROECKER *et al.*, 1985), both of which were approximately 50‰, indicates that radiocarbon is being incorporated into Antarctic mollusc shells in equilibrium with ambient seawater

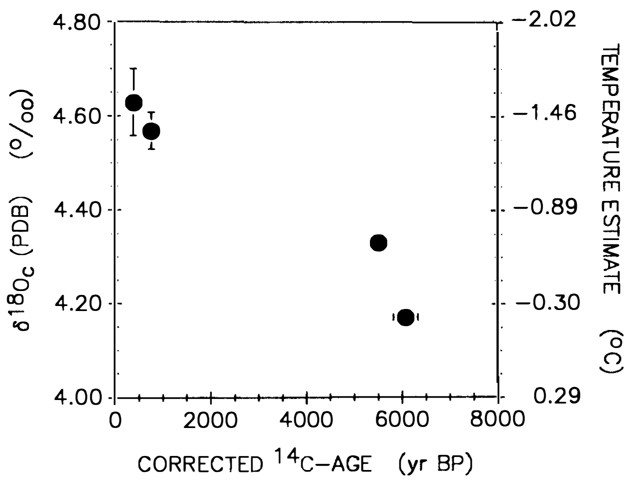

Fig. 6. Shell oxygen isotope ratios based on Adamussium *fossils which were collected from emerged Holocene beaches in Terra Nova Bay, Antarctica, by* BARONI *et al. (1991). Fossil shell radiocarbon ages were corrected by a factor of 1400 ± 100 years and temperature estimates were derived from eq. (2) (see text).*

in the Southern Ocean. Moreover, the data in Table 4 indicate that 1400 ± 100 years is generally appropriate as a radiocarbon reservoir correction for Antarctic molluscs during the Holocene. To further resolve the radiocarbon-age variability between species and regions in the Southern Ocean (OMOTO, 1983; GORDON and HARKNESS, 1992), additional radiocarbon dates on pre-nuclear Antarctic molluscs from other museum collections should be measured.

4.4. Oxygen isotope geochemistry of Holocene fossil shells

Bulk shell $\delta^{18}O_c$ (PDB) values in *Adamussium* fossils from emerged Holocene beaches at Terra Nova Bay were measured by BARONI *et al.* (1991). Paleotemperature estimates (eq. (2)) based on these data indicate that the bulk shell samples accurately reflect modern sea water temperatures which generally are lower than −1.6°C in the surface waters of the Ross Sea (LITTLEPAGE, 1965; BARRY, 1988; JACOBS *et al.*, 1985).

The paleotemperature estimates further suggest that seawater temperatures 5000 to 6000 ^{14}C yr BP (corrected) were nearly 1.5°C warmer than today (Fig. 6). High-resolution data from Antarctic ice cores, however, indicate that the maximum temperature range in the atmosphere around the continent during the entire Holocene was only 1°C (LORIUS *et al.*, 1979; CIAS *et al.*, 1992). These ice-core temperatures suggest that the additional 0.5°C in the temperature estimates from the fossil shells was associated with more meltwater input along the Antarctic coastline during the middle Holocene than at present.

5. Conclusions

1) Shells of the Antarctic scallop (*Adamussium colbecki*) at Explorers Cove contain complementary trace element, unit cell and oxygen isotope signatures of glacial meltwater. Relationships between these different geochemical parameters should be

investigated further to detect the presence of meltwater from the Antarctic ice sheets earlier in the Holocene.

2) The volume of glacial meltwater runoff into Explorers Cove during the summer, along with the $\delta^{18}O_w$ (SMOW) values in the seawater, were accurately predicted from the isotopic composition of live *Adamussium* shells in the nearshore environment. Similar studies should be conducted in other Antarctic coastal areas to establish baselines for interpreting the oxygen isotopic signatures of Holocene fossils around the continent.

3) Mollusc shells that are living in nearshore marine environments and have fossils in adjacent Holocene beaches provide a geochemical framework for interpreting meltwater impacts in Antarctic coastal areas during the last 10000 years or more.

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Appendix 1. Inventory of Holocene marine fossils in Antarctic beaches.

Fossil species	0°–60°W	60°–120°W	120°–180°W	180°–120°E	120°–60°E	60°–0°E
Algae						
Achnanthes brevipes					x[18]	
Actinocyclus oculatus					x[18]	
Actinocyclus sp.					x[18]	
Archaeolithothamnion sp.					x[24]	
Asteromphalus parvulus					x[18]	
Cocconeis antiqua					x[18]	
Cocconeis costata					x[18]	
Cocconeis extravagans					x[18]	
Cocconeis fasciolata					x[18]	
Cocconeis imperatrix					x[18]	
Cocconeis pinnata					x[18]	
Coscinodiscus apiculatus					x[18]	
Coscinodiscus biradiatus					x[18]	
Coscinodiscus moelleri					x[18]	
Coscinodiscus oculus					x[18]	
Coscinodiscus symbolophorus					x[18]	
Diploneis graeffi					x[18]	
Diploneis smithii					x[18]	
Diploneis sejuncta					x[18]	
Diploneis splendida					x[18]	
Eucampia balaustium					x[18]	
Fragiariopsis curta					x[18]	
Grammatophora arcuata					x[18]	
Hyalodiscus radiatus					x[18]	
Licophora communis					x[18]	
Melosira omma					x[18]	
Melosira sulcata					x[18]	
Navicula directa					x[18]	
Navicula grevillei					x[18]	
Pinnularia quadraterea					x[18]	
Plagiogramma fenestra					x[18]	
Stephanopyxis turris					x[18]	
Stephanopyxis sp.					x[18]	
Thalassiosira gravida					x[18]	
Trachyneis aspera					x[18]	
Corralinacea						x[6,21]
unidentified					x[9,19]	
Foraminifera						
Anglogerina sp.				x[2]		x[11]
Astrononion antarcticus				x[2]		x[11]
Bolivina pseudopunctata						x[11]
Bolivina earlandi					x[18]	
Bolivina sp.						x[11]
Cassidulina crasa					x[18]	x[11]
Cassidulina subglobosa					x[18]	
Cassidulinoides parkerianus						x[11]
Cassidulinoides porrectus						a[11]

x present, c common, a abundant.

Appendix 1 (continued).

Fossil species	Location of Antarctic beaches					
	0°–60°W	60°–120°W	120°–180°W	180°–120°E	120°–60°E	60°–0°E
Foraminifera (cont'd.)						
Cibicides lobatulus					x[18]	
Cibicides refulgens				c[2]		c[11]
Discorbis globularis					x[18]	
Ehrenbergina glabra				x[2]		a[11]
Elphidium orbiculare						a[11]
Epistominella exigua				x[2]		a[11]
Epistominella patagonica					x[18]	
Fissurina annectens					x[18]	
Fissurina sp.				x[2]		
Fursenkoina sp.				x[2]		
Glandulina antarctica						x[11]
Globocassidulina sp.				c[2]		
Lagena sp.				x[2]		
Laryngosigma hyalascidia					x[18]	
Lingulina sp.					x[18]	
Miliammina sp.				x[2]		
Nonionella bradyi				x[2]		x[11]
Nonionella iridea					x[18]	
Oolina squamosa					x[18]	
Oolina sp.				x[2]		
Patellina corrugata					x[18]	x[11]
Patellinoides conica						x[11]
Pullenia sp.				x[2]		
Pseudobulimina chapmani						x[11]
Pyrgo elongata						x[11]
Quinqueloculina seminulum					x[18]	
Quinqueloculina serra					x[18]	
Quinqueloculinella sp.						x[11]
Rosalina sp.						c[11]
Sigmoilina sp.						x[11]
Triculina lamellidens					x[18]	
Trochammina antarctica					x[18]	
Trochammina squamata					x[18]	
Virgulina schreibersiana					x[18]	
Virgulina sp.						x[11]
unidentified				c[1]		x[8]
Bryozoa						
Cellaria sp.				c[15]		
unidentified				c[15]		
Porifera						
Tetilla leptoderma					x[20]	
Jophon radiatus					x[20]	
Micale sp.					x[20]	
Tetractinellida				c[15]		
unidentified				c[15]	x[10]	

x present, c common, a abundant.

Appendix 1 (continued).

Fossil species	Location of Antarctic beaches 0°–60°W	60°–120°W	120°–180°W	180°–120°E	120°–60°E	60°–0°E
Annelida						
Helicosiphon biscoensis					x[10]	
Hydroides sp.					x[10]	
Serpula narconensis				x[15]	a[9,10,19] x[10]	
Serpula sp.				c[15]	a[10]	
Spirorbis sp.				x[1]	x[10]	
Serpulidae				x[1,7] c[14]	c[9,20]	x[8]
unidentified					x[9]	x[21,25]
Mollusca						
Adamussium colbecki				a[1,14,16] c[4,7,12,15]	c[9]	c[8,11,21]
Axinopsida sp.					x[18]	
Cerithiopsilla antarctica				x[15]		
Gardineria antarctica				x[15]		
Hexelasma antarcticum				x[15]		
Iothia copperingeri					x[10]	
Laternula elliptica				c[1,12,14,15]	a[9,10,18,19,20,22]	c[8,11,21]
Lima sp.				x[1,15]		
Limatula hodgsoni				c[15]	x[10,18,19,20]	
Limopsis marionensis				c[14]	x[10]	
Liothyrina antarctica				x[15]		
Lorabela plictula				x[1]		
Malletia pellucida					x[10]	
Margarella sp.					x[10]	
Margarites refulgens					x[10]	
Mysella gibbosa					x[10]	
Neobuccinum eatoni				c[1]	x[10]	
Pilidium antarctica				x[15]		
Philine apertisima				c[1]		
Philobrya sublaevis					x[10]	
Powellisetia deserta					x[10]	
Subnoba contigua				x[1]		
Submargarita crebribrulata				x[15]		
Stoa sp.					x[10]	
Thracia meridionalis				c[1] x[15]	x[10,18,20]	
Trophon longstaffi				x[15]		
Trophon schackletoni					x[20]	
Pelecypoda				x[1,16]		
Polyplacophora				x[15]		
unidentified	x[5,13]			x[1,7,14,15,16]	x[9,10,25]	x[8,21]
Echinodermata						
Odontaster validus				x[1]		
Psilaster charcoti				x[1]		
Sterichinus neumayeri				c[1]		
Ophiouroidea				a[1]		
Echinoidea				x[15]		x[11]

x present, c common, a abundant.

Appendix 1 (continued).

Fossil species	Location of Antarctic beaches					
	0°–60°W	60°–120°W	120°–180°W	180°–120°E	120°–60°E	60°–0°E
Arthoropoda						
Bathylasma corolliforme		x[3]		x[15]		
Cirripedia				c[14,16,17]		
Pycnogonida				x[1]		
Ostracoda				x[1]		x[11]
Amphipoda				x[1]		
Crustacea				x[15]		
Anthozoa				x[15]		
Pisces						
Teleostea				x[1]		
Aves						
Pygoscelis adelie				x[1,4,7]	x[10] a[23]	
Aptenodytes forsteri					x[10]	
Macronectes gigantea					x[10]	
Penguins				a[16,17]		
Mammalia						
Hydrurga leptonyx					x[10,20]	
Leptonychotes weddelli					x[10]	
Lopodon carcinophagus					x[10]	
Mirounga leonina	x[13]				x[10,12,20]	
Cetacea	x[5,13]			x[1]		
Pinnipedia	x[13]			x[1,7,15,17]		x[8]

x present, c common, a abundant

References: (1) Chapman-Smith, 1981, (2) Webb and Wrenn, 1975, (3) Clapperton and Sugden, 1982, (4) Stuiver *et al.*, 1981, (5) Shotton *et al.*, 1969, (6) Cameron and Goldthwaite, 1961, (7) Baroni and Orombelli, 1989, (8) Omoto, 1977, (9) Adamson and Pickard, 1983, (10) Pickard, 1985, (11) Meguro *et al.*, 1964, (12) Nichols, 1968, (13) Curl, 1980, (14) Baroni, 1990, (15) Speden, 1962, (16) Baroni and Orombelli, 1991, (17) Baroni and Orombelli, 1987, (18) Zhang and Peterson, 1984, (19) Adamson and Pickard, 1986, (20) Korotkevich, 1971, (21) Yoshida, 1983, (22) Adamson and Colhoun, 1992, (23) Goodwin, 1993, (24) Cameron, 1964, (25) Fitzsimons and Domack, 1993.

Appendix 2. Inventory of in situ molluscan fossil radiocarbon ages and elevations in Holocene beaches around Antarctica.

Laboratory number	Mollusc species[1]	Latitude	Longitude (m.a.s.l)[2]	Beach elevation (yr BP)[3]	^{14}C age uncorrected	Reference
			Sôya Coast			
not available	Ac	69°00′S	39°35′E	3.5	3840±110	Meguro *et al.*, 1963
not available	Ac	69°14′S	39°39′E	1.5	4290±110	Omoto, 1977
not available	Le	69°14′S	39°40′E	1.5	3840± 90	Omoto, 1977
not available	Le	69°29′S	39°40′E	14	7450±135	Omoto, 1977
not available	Ac	69°03′S	39°35′E	2.0	2510±110	Omoto, 1977
not available	Ac	69°03′S	39°35′E	0.8	2040± 90	Yoshida, 1983
Th 020	Le	69°14′S	39°40′E	14	6020±175	Omoto *et al.*, 1974
Th 021	Ac	69°03′S	39°35′E	2	1450±110	Omoto *et al.*, 1974
Th 044	Ac	69°11′S	39°41′E	1.5	3305±130	Omoto, 1976
Th 186	Le	69°11′S	39°41′E	3	3120±110	Omoto, 1978
GaK 2034	Ac	69°29′S	39°40′E	8	4700±100	Yoshida, 1983
GaK 2035	Ac	69°29′S	39°40′E	1.8	3600±100	Yoshida, 1983
GaK 2039	Le	69°29′S	39°40′E	0.5	3180±250	Yoshida, 1983
GaK 4150	Ac	69°14′S	39°40′E	6	10250±210	Yoshida, 1983
GaK 4151	Ac	69°14′S	39°40′E	1.5	4290± 90	Yoshida, 1983
GaK 4850	Le	69°14′S	39°40′E	1.5	3840± 90	Yoshida, 1983
GaK 5834	Le	69°29′S	39°40′E	4	2540±160	Yoshida, 1983
GaK 5835	Le	69°29′S	39°40′E	11	5580±180	Yoshida, 1983
GaK 5836	Le	69°29′S	39°40′E	3	3370±120	Yoshida, 1983
GaK 5839	Le	69°30′S	41°00′E	10	7730±110	Yoshida, 1983
GaK 5841	Le	69°29′S	39°40′E	6	4430± 90	Yoshida, 1983
GaK 6374	Le	69°14′S	39°40′E	5.1	4570±120	Omoto, 1977
GaK 6387	Le	69°14′S	39°40′E	1.4	1030±100	Omoto, 1977
GaK 6388	Le	69°14′S	39°40′E	5.5	3730±220	Omoto, 1977
GaK 6389	Le	69°29′S	39°40′E	11.7	5370±160	Omoto, 1977
GaK 6390	Le	69°29′S	39°40′E	4.7	8130±200	Omoto, 1977
GaK 6391	Le	69°29′S	39°40′E	12	6700±180	Omoto, 1977
GaK 6392	Le	69°29′S	39°40′E	15.5	5860±170	Omoto, 1977
			Vestfold Hills			
ANU 1011	Le	68°33′S	78°07′E	2.6	4710± 70	Adamson and Pickard, 1986
Beta 4766	Le	68°36′S	78°10′E	2.6	5795± 85	Pickard, 1985
Beta 4767	Le	68°36′S	78°10′E	3	7370± 95	Pickard, 1985
Beta 4768	Ac	68°36′S	78°10′E	2.6	7305±130	Pickard, 1985
SUA 1239	Le	68°34′S	78°09′E	2.6	5440±110	Pickard and Adamson, 1983
SUA 1411	Le	68°39′S	77°55′E	2	2410± 90	Adamson and Pickard, 1986
SUA 2026	Le	68°36′S	78°09′E	5.5	7590± 80	Adamson and Pickard, 1986
SUA 2027	Le	68°29′S	78°21′E	2	6910±150	Adamson and Pickard, 1986
SUA 2030	Le	68°31′S	78°20′E	1.8	6850±160	Pickard and Seppelt, 1984
ZDL 66	Le	68°39′S	77°55′E	3	3325±103	Zhang *et al.*, 1983
ZDL 70	Le	68°36′S	78°10′E	2:6	6100±108	Zhang *et al.*, 1983
ZDL 78	Le	68°32′S	78°16′E	6.0?	6141± 90	Zhang *et al.*, 1983
ZDL 79	Le	68°34′S	78°03′E	6.0?	5600± 77	Zhang *et al.*, 1983
ZDL 80	Le	68°34′S	78°16′E	6.0?	6632±118	Zhang *et al.*, 1983

Appendix 2. (Continued).

Laboratory number	Mollusc species[1]	Latitude	Longitude (m.a.s.l)[2]	Beach elevation (yr BP)[3]	^{14}C age uncorrected	Reference
			Bunger Hills			
Beta 15828	Le	66°10′S	101°E	2.8	8950±490	ADAMSON and COLHOUN, 1992
Beta 15829	Le	66°10′S	101°E	3.5	6900±120	ADAMSON and COLHOUN, 1992
Beta 15830	Le	66°10′S	101°E	4	5630± 90	ADAMSON and COLHOUN, 1992
Beta 15831	Le	66°10′S	101°E	2	6880±160	ADAMSON and COLHOUN, 1992
Beta 15832	Le	66°10′S	101°E	5.2	6250±120	ADAMSON and COLHOUN, 1992
Beta 17524	Le	66°10′S	101°E	1.3	6210±100	ADAMSON and COLHOUN, 1992
Beta 17525	Le	66°10′S	101°E	2.6	6010±100	ADAMSON and COLHOUN, 1992
Beta 17526	Le	66°10′S	101°E	3	4960±120	ADAMSON and COLHOUN, 1992
Beta 17527	Le	66°10′S	101°E	2.2	6500±130	ADAMSON and COLHOUN, 1992
			Terra Nova Bay			
GX 13627	Ac	74°52′S	163°54′E	9	6815± 90	BARONI and OROMBELLI, 1987
GX 14066	Mix	74°52′S	164°54′E	10.5	6915±230	BARONI and OROMBELLI, 1991
GX 14069	Mix	74°52′S	164°54′E	14.5	7505±230	BARONI and OROMBELLI, 1991
GX 14070	Mix	74°52′S	164°54′E	12.5	7480±260	BARONI and OROMBELLI, 1991
GX 14627	Le	74°52′S	164°54′E	10.5	6645± 95	BARONI and OROMBELLI, 1991
GX 14628	Le	74°52′S	164°54′E	12.5	6890±100	BARONI and OROMBELLI, 1991
GX 14823	Le	74°52′S	164°54′E	9	6935±100	BARONI and OROMBELLI, 1991
GX 14824	Ac	74°52′S	164°54′E	9.5	6765±355	BARONI and OROMBELLI, 1991
GX 14825	Ac	74°52′S	164°54′E	10.5	6620±190	BARONI and OROMBELLI, 1991
			West McMurdo Sound			
QL 72	Ac	77°38′S	166°25′E	6.0	6430± 70	STUIVER *et al.*, 1981
QL 96	Ac	77°38′S	166°25′E	4.5	6350± 60	STUIVER *et al.*, 1981
QL 137	Ac	77°38′S	166°25′E	5.7	6050± 70	STUIVER *et al.*, 1981
QL 138	Ac	77°38′S	166°25′E	7.5	5800± 70	STUIVER *et al.*, 1981
QL 139	Ac	77°38′S	166°25′E	5.0	5240± 40	STUIVER *et al.*, 1981
QL 153	Ac	77°38′S	166°25′E	1.4	5200± 60	STUIVER *et al.*, 1981
QL 154	Ac	77°38′S	166°25′E	3.3	5630± 60	STUIVER *et al.*, 1981
QL 155	Ac	77°38′S	166°25′E	1.0	5310± 60	STUIVER *et al.*, 1981
QL 156	Ac	77°38′S	166°25′E	2.2	5090± 50	STUIVER *et al.*, 1981
QL 157	Ac	77°38′S	166°25′E	4.5	6150± 80	STUIVER *et al.*, 1981
QL 158	Ac	77°38′S	166°25′E	4.2	5860± 70	STUIVER *et al.*, 1981
QL 159	Ac	77°38′S	166°25′E	1.9	5350± 70	STUIVER *et al.*, 1981
QL 160	Ac	77°38′S	166°25′E	0.5	5770± 50	STUIVER *et al.*, 1981
QL 161	Ac	77°38′S	166°25′E	1.7	5500± 70	STUIVER *et al.*, 1981
QL 162	Ac	77°38′S	166°25′E	5.3	5970± 70	STUIVER *et al.*, 1981
QL 163	Ac	77°38′S	166°25′E	8.1	5400± 60	STUIVER *et al.*, 1981
QL 164	Ac	77°38′S	166°25′E	0.5	5760± 60	STUIVER *et al.*, 1981
QL 165	Ac	77°38′S	166°25′E	2.9	4620± 60	STUIVER *et al.*, 1981
QL 1042	Ac	77°38′S	166°25′E	4.0	6120± 50	STUIVER *et al.*, 1981
			James Ross Island, Antarctic Peninsula			
Lu 2876	Le	63°45′S	58°30′W	8	7920± 60	INGOLFSSON *et al.*, 1992
Lu 2877	Le	63°45′S	58°30′W	-	8460± 90	INGOLFSSON *et al.*, 1992

(1) Ac *Adamussium colbecki*, Le *Laternula elliptica*, Mix Mixed *Laternula* and *Adamussium*. (2) m.a.s.l. meters above sea level, based on the 1 m elevation of mean high tide. (3) yr BP Year Before Present (mean ± 1 standard deviation).